Tuned Liquid Column Dampers with Period Adjustment Equipment for Earthquake Vibrations of High-rise Structures

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Abstract

This paper investigates the application of a bi-directional vibration system, namely Tuned Liquid Column Damper with Period Adjustment equipment (TLCD-PA), which is used to decrease the vibrations of high-rise buildings due to earthquake oscillations. The TLCD-PA is a two degree-of-freedom (2DOF) system consists of two U-shaped tubes filled with water (2TLCDs) and a pendulum. The second TLCD, namely Period Adjustment equipment (PA), is smaller than the first one and placed above it. The two TLCDs are connected through the air tubes at the top of vertical columns. The liquid displacement in the PA system moves the plate at the middle radially, which is connected to the pendulum. The liquid columns, the air tubes and the pendulum provide spring stiffness for the system. On the other hand, the liquid movement in the two TLCDs provides nonlinear damping for the equipment. The liquid mass in the two TLCDs and the pendulum provide the required mass for the system. Therefore, this type of damper consists of many adjustable parameters that help for the better tuning of frequency and damping coefficients.

In this paper, the effect of various important parameters of the TLCD-PA on the earthquake vibrations of tall buildings is investigated. The structure is modeled as a single DOF system equipped with TLCD-PA at the top of the building. Kobe earthquake data is employed for the modeling of earthquake oscillations, and the nonlinear Newmark method is applied for the displacement, velocity and acceleration calculations. The effects of area ratios and length ratios for the U-shaped tubes of two TLCDs are investigated. Moreover, the effects of pendulum parameters such as mass, spring stiffness and length of the pendulum are discussed. The frequency effects of TLCD and PA equipment are also studied. It is shown that the TLCD-PA is a useful system for the reduction of building vibrations. It is also shown that how the various parameters assist the designers to the better adjustment of the TLCD-PA system. This study helps the researchers to the better understanding of the TLCD-PA system, and leads the designers to achieve more efficient dampers for the high-rise buildings.

Keywords: Tuned Liquid Column Damper, Period Adjustment Equipment, High-rise Structure, Earthquake Vibration.

1. INTRODUCTION

In recent years, the construction of new high-rise buildings are facilitated and developed in many countries due to the lighter and stronger materials. These tall and slender buildings are usually subjected to wind and earthquake vibrations, which may cause structural failure, discomfort to occupants and malfunction of equipment. Therefore, mitigation of wind and earthquake induced vibrations by using supplemental damping devices has been widely investigated.

Among passive control devices, tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) have been widely employed for decreasing the wind and earthquake induced vibration of tall building structures. The original idea of tuned liquid column damper (TLCD) was developed by Sakai et al. [1] for suppression of horizontal motion of structures. After that, quite a few research papers, namely Xu et al. [2], Hitchcock et al. [3], Balendra et al. [4], Min et al. [5] and Felix et al. [6], have verified its effectiveness for suppressing wind induced horizontal responses, among whom Hitchcock et al. [3] even investigated a general type of TLCDs that have non uniform cross-sections in the horizontal and vertical columns, termed as liquid column vibration absorber (LCVA). Recently, the application of TLCDs was further extended to the suppression of pitching motion for bridge decks (e.g., Xue et al. [7] and Wu et al. [8]). For the application to the control of horizontal motion toward implementation, some researchers have spent efforts on determining optimal TLCD designs, such as Chang et al. [9] and Chang [10] on undamped structures, Wu et al. [11,12] on damped structures, and Yalla et al. [13] on both damped and undamped structures. Their results of optimal parameters is provided for the case that loading on buildings is white-noise type, such as wide-banded along wind loads.

There are also some applications of TLCD technologies, including period adjustment mechanisms. By providing a Tuned Liquid Column Damper with Period Adjustment Equipment (TLCD-PA), the behavior of
the liquid motion in the liquid column damper may be regulated [14]. This system was introduced and developed by Teramura and Yoshida firstly [15], but few works referred to it; and the effects of different parameters involved in the system is not investigated in the papers yet. Such a system has been installed in the top floor of the 26 story Hotel Cosima, now called Hotel Sofitel in Tokyo [16].

Considering soil effects, the structure response differs from the fixed base model. Various investigations are performed to study the soil-structure interaction (SSI) effects. For example, frequency domain analysis was performed by Xu and Kwok [17] to obtain the wind induced vibrations of soil-structure-damper system. Moreover, the frequency independent expressions are proposed by wolf [18] to determine the swaying and rocking dashpots, and the related springs of a rigid circular foundation. Recently, Liu et al. [19] developed a mathematical model for time domain analysis of wind induced oscillations of a tall building with TMD considering soil effects. Soheili et al. [20] investigated the optimized parameters for the tuned mass dampers to decrease the earthquake vibrations of high-rise buildings including SSI effects.

Although numerous works are performed concerning TLCD effects, few investigations are carried out on the time response of high-rise buildings due to earthquake excitations. In fact, most researches are focused on the wind load effects employing the white noise loads. The time domain analysis of structures is an advantageous process for the better understanding of earthquake oscillations and TLCD-PA characteristics. Since the TLCDs are nonlinear devices, the nonlinear methods; such as the nonlinear Newmark method, should be employed to investigate the vibration behavior of the structures [21, 22].

In this paper, the mathematical model of structure with TLCD-PA equipment is developed for calculating the earthquake responses. The model is employed to obtain the time response of 40 story building using TLCD-PA device. The effects of different parameters such as the cross sectional ratios, length ratios, head loss coefficients and pendulum parameters are investigated. The parameters are calculated with and without pendulum effects, using the multiple DOF model for the structure. This study may improve the researchers’ knowledge of earthquake oscillations for a building with TLCD-PA equipment.

2. MODELING OF TALL BUILDINGS

Figure 1 shows the structure with TLCD-PA equipment. Mass, stiffness and damping of the structure are assumed as \( M \), \( K \) and \( C \), respectively. The time history of building displacement is indicated by \( x \), while the time history of liquid displacement for the vertical and horizontal columns of TLCD are shown as \( y_v \) and \( y_r \), respectively; and for the PA equipment is presented as \( y_b \). Figure 2 shows the TLCD-PA configuration.

The kinetic energy for the structure is obtained in the following form:

\[
T = (1/2)\rho a \left( L_c - y_v \right) (y_v^2 + \dot{x}^2) + (1/2)\rho a \left( L_c + y_v \right) (\dot{y}_v^2 + \dot{x}^2) + (1/2)\rho a \left( L_v \right) x^2 + (1/2)\rho a \left( L_h \right) (\dot{x} + \dot{y}_b)^2
\]

\[
+ (1/2)\rho a \left( L_c \right) (\dot{y}_v^2 + \dot{x}^2) + (1/2)\rho a \left( L_v \right) (\dot{x})^2 + (1/2)\rho a \left( L_h \right) (\dot{x} + \dot{y}_b)^2
\]

(1)

In this equation, \( A_v \) and \( A_h \) represent the cross sectional area of vertical and horizontal columns of TLCD, respectively; while \( A_r \) show the cross sectional area of PA device. Similarly, \( L_c \) and \( L_h \) indicate the vertical and horizontal column length of TLCD, respectively; and \( L_v \) denotes the total liquid length in PA equipment. The pendulum mass, length and angular rotation are assumed as \( m_p \), \( L_p \) and \( \theta \), respectively; while the valve mass is defined as \( m_v \), and \( \rho \) is the fluid density.

The potential energy for the structure can be calculated as follows:

\[
U = (1/2)\rho g A_v \left( L_c - y_v \right) \left( L_c + y_v \right) + (1/2)\rho g A_v \left( L_c - y_v \right) \left( L_c + y_v \right) + (1/2)K_x \left( L_c \right) \left( \dot{y}_v \right)^2
\]

\[
+ (1/2)k_{co} \left( L_{co} \right)^2 - m_p L_{co} \left( 1 - \cos \theta \right) + m_v g h_r \left( 1 - \cos \theta \right) + 2 \times (1/2)(\eta P_0 / V_0) (A_2 y_v - A_r y_r)^2
\]

(2)
In which, $L'_v$ is the vertical length of liquid in PA device, $k_{co}$ and $L_{co}$ denotes the spring stiffness of pendulum and its distance to the main shaft; respectively, and $h_r$ refers to the valve height. In addition, $P_0$ and $V_0$ indicate the pressure and volume of the air room, respectively, while $n=1.4$ shows the specific heat of air. Considering the orifice valve, the valve dimensions could be set in such a form that:

$$\theta = \frac{y_r}{h_r}$$

(3)

The non-conservative forces are calculated in the following form:

$$Q = -C\ddot{x} - \frac{1}{2}\rho A_h \eta |\dot{y}_h|\dot{y}_h - \frac{1}{2}\rho A_r \eta |\dot{y}_r|\dot{y}_r$$

(4)

The parameters $\eta_h$ and $\eta_r$ represent the head loss coefficient for the TLCD and PA equipment, respectively. The cross sectional ratios of the TLCD and PA columns versus horizontal column are defined as follows:

$$n_1 = \frac{A_z}{A_h}$$

$$n_2 = \frac{A_r}{A_h}$$

(5)

Similarly, the length ratios of the TLCD and PA columns versus horizontal column are defined as follows:

$$n_1 = \frac{L_z}{L_h}$$

$$n_2 = \frac{L_r}{L_h}$$

(6)

The continuity condition between the horizontal and vertical column of TLCD yields:

$$\dot{y}_h = \eta \dot{y}_z$$

(7)

Substituting $A_z$, $A_r$, $L_z$, $L_r$ and $\dot{y}_h$ in kinetic energy, potential energy and non-conservative force relations, these equations could be stated based on the area and length ratios. Using Lagrange’s equation, the equation of motion for the building shown in Figure 1 is obtained as follows [21,23]:

$$\left[ m \right] \ddot{\{x(t)\}} + \left[ c \right] \{\dot{x}(t)\} + \left[ k \right] \{x(t)\} = -\left[ m^* \right] \ddot{\{u_g\}} / L_k$$

(8)

where $[m]$, $[c]$ and $[k]$ denote mass, damping and stiffness of the oscillating system. $[m^*]$ indicates acceleration mass matrix for earthquake and $\ddot{\{u_g\}}$ is the earthquake acceleration. Considering the TLCD-PA equipment, the structure is a 3 DOF oscillatory system. Using Lagrange’s equation, and dividing the equations by $h_A$, $m$, $c$ and $k$; mass, damping and stiffness matrices are obtained in the following form [15, 23]:

$$[m] = \begin{bmatrix}
    l_v & 0 & 0 \\
    0 & \frac{r_v}{n_2} L_h + \frac{m_{pe}}{\rho A_h} & L_h \\
    L_h & 0 & \frac{L'_v}{n_1} + \frac{r_v}{n_1} L_h + \frac{m_{pe} + M}{\rho A_h}
\end{bmatrix}$$

(9)

$$[k] = \begin{bmatrix}
    2g + k_1 n_1 & -k_1 r_v & 0 \\
    -k_1 r_v & 2g \frac{r_v}{n_1} + \frac{k_{pe}}{\rho A_h} + k_1 \frac{r_v^2}{n_1} & 0 \\
    0 & 0 & \frac{K}{\rho A_h}
\end{bmatrix}$$

(10)

$$[c] = \begin{bmatrix}
    \frac{1}{2} \eta_h |\dot{y}_z| & 0 & 0 \\
    0 & \frac{1}{2} \eta_r |\dot{y}_r| & 0 \\
    0 & 0 & C / \rho A_h
\end{bmatrix}$$

(11)

$$[m^*] = \begin{bmatrix}
    0 & 0 & L_h \\
    0 & 0 & 0 \\
    0 & \frac{L'_v}{n_1} + \frac{r_v}{n_1} L_h + \frac{m_{pe} + M}{\rho A_h}
\end{bmatrix}$$

(12)

In the mentioned equations, $l_v$ and $l'_v$ respectively show the effective and semi-effective length of the TLCD, which are calculated as follows:

$$l_v = 2L_v + n_1 L_h$$

$$l'_v = 2n_1 L_v + L_h$$

(13)
Furthermore, \( m_{pe} \) and \( k_{pe} \) are the effective mass and stiffness of pendulum, which are defined as follows:

\[
m_{pe} = m_p \left( \frac{L_p}{h_r} \right)^2 + m_v
\]

\[
k_{pe} = k_{co} \left( \frac{L_{co}}{h_r} \right)^2 - m_p g \left( \frac{L_p}{h_r} \right)^2 + m_v g / h_r
\]

The parameter \( m_{pv} \) is the total mass of valve and pendulum, in the following form:

\[
m_{pv} = m_p + m_v
\]

Finally, the parameter \( k_1 \) denotes the air stiffness as follows:

\[
k_1 = \left( \frac{2n_0}{\rho V_0} \right) A_h
\]

It is clear that the damping matrix is a nonlinear one, due to the nonlinear damping of TLCD. The natural frequencies of the TLCD, PA and the structure are obtained respectively in the following form:

\[
\omega_{n1} = \sqrt{\frac{2g + k_1 \eta}{\eta_1}} = \sqrt{\frac{2g}{L_h} + k_1 \eta_1} \left/ \left( 2n_1 + \eta_1 \right) \right.
\]

\[
\omega_{n2} = \frac{\sqrt{2g + \frac{k_{pe}}{\rho(A_h)} + k_a L_h \frac{r_2}{\eta_1} \left/ \left( \frac{r_2}{\eta_1} n_2 L_h + \frac{m_{pe}}{\rho(A_h)} \right) \right.}}{\sqrt{2g + \frac{k_{pe}}{\rho(A_h)} + k_a L_h \frac{r_2}{\eta_1} \left/ \left( \frac{r_2}{\eta_1} n_2 L_h + \frac{m_{pe}}{\rho(A_h)} \right) \right.}}
\]

\[
\omega_s = \frac{2\pi}{T_s} = \sqrt{\frac{K}{M}}
\]

In which, the parameters \( \mu_1 \) and \( \mu_2 \) are the non-dimensional mass coefficients defined as follows:

\[
\mu_1 = \frac{\rho L_h}{M}
\]

\[
\mu_2 = \frac{m_{pe}}{M}
\]

also:

\[
k_a = \left( \frac{2n_0}{\rho V_0} \right) A_h = k_1 L_h
\]

The non-dimensional displacement vector \( \{x(t)\} \) including displacement of building as well as TLCD-PA motion can be represented in the following form:

\[
\{x(t)\} = \begin{bmatrix} y_1(t) / L_h & y_2(t) / L_h & x(t) / L_h \end{bmatrix}^T
\]

The complete non-dimensionalized form of the mass, damping and stiffness matrices is stated as follows:

\[
[m] = \begin{bmatrix} 1 & 0 & \frac{1}{2n_1 + \eta_1} \\ 0 & 1 & 0 \\ \mu_1 \eta_1 & 0 & \mu_1 n_3 + \mu_1 r_2 n_2 + \mu_3 + 1 \end{bmatrix}
\]

\[
[c] = \begin{bmatrix} \frac{1}{2} \frac{n_1 \eta_1}{n_1 + \eta_1} \dot{y}_1 & 0 & 0 \\ 0 & \frac{1}{2} \frac{r_2 \eta_2}{r_2 n_2 + \mu_2 / \mu_1} \dot{y}_2 & 0 \\ 0 & 0 & 2 \omega_s \end{bmatrix}
\]

\[
[k] = \begin{bmatrix} \omega_{n1}^2 & -\frac{k_a r_2}{2n_1 + \eta_1} & 0 \\ -\frac{k_a \eta_1}{n_2 + \mu_2 / \mu_1 r_2} & \omega_{n2}^2 & 0 \\ 0 & 0 & \omega_s^2 \end{bmatrix}
\]

\[
[m^*] = \begin{bmatrix} \frac{1}{2n_1 + \eta_1} & 0 & 0 \\ 0 & \frac{1}{\eta_1} & 0 \\ 0 & 0 & \mu_1 n_3 + \mu_1 r_2 n_2 + \mu_3 + 1 \end{bmatrix}
\]
In which, $\mu_3$ and $n_3$ are the non-dimensionalized coefficients defined in the following form:

$$\mu_3 = \frac{m_{pv}}{M}$$

$$n_3 = \frac{L_h}{L_h} = 2n_1 + 1$$

According to Rayleigh proportional damping, the damping matrix of N-storey structure yields as follows:

$$[c]_{N\times N} = A_0[m]_{N\times N} + A_1[k]_{N\times N}$$

in which $A_0$ and $A_1$ are Rayleigh damping coefficients.

In this paper, Kobe earthquake acceleration spectrum is applied to the structure, and time response of TLCD and building are calculated based on nonlinear Newmark integration method [22].

### 3. ILLUSTRATIVE EXAMPLE

The methodology outlined previously is employed to calculate the structural response of a 40-storey building with TLCD. Table 1 shows the structure parameters based on the generalized mass of the fundamental mode for the unit modal participation factor [19]. The TLCD is installed on the top of building for the better damping of vibrations. The search area settings are shown in Table 4.

#### Table 1: Structure parameters [19]

| No. of stories | 40 |
| Storey Height ($Z_i$) | 4 m |
| Unit Modal Mass ($M$) | $3.10 \times 10^7$ kg |
| First Natural Frequency ($\omega_s$) | 1.65 rad/s (0.263 Hz) |
| Structure Stiffness ($K$) | $8.44 \times 10^7$ N/m |
| Structure Damping ($C$) | $1.69 \times 10^6$ Ns/m |
| Damping Coefficient ($\xi$) | 0.0165 |
| Rayleigh Damping Coefficients | $A_0 = 0$ , $A_1 = 0.02$ |

#### Table 2: The parameter settings for TLCD-PA

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.1 \leq r_1$ , $r_2 \leq 3.1$</td>
<td></td>
</tr>
<tr>
<td>$0.1 \leq n_1$ , $n_2 \leq 3.1$</td>
<td></td>
</tr>
<tr>
<td>$0 \leq \eta_h$ , $\eta_r \leq 50$</td>
<td></td>
</tr>
<tr>
<td>$1 \leq L_h$ (m)</td>
<td>$\leq 40$</td>
</tr>
<tr>
<td>$200 \leq m_p$ (kg)</td>
<td>$\leq 200 \times 10^3$</td>
</tr>
<tr>
<td>$200 \leq k_a$ (N/m)</td>
<td>$\leq 200 \times 10^3$</td>
</tr>
<tr>
<td>$1 \leq L_p$ (m)</td>
<td>$\leq 10$</td>
</tr>
</tbody>
</table>

![Figure 3: Kobe earthquake acceleration spectrum](image)

As mentioned before, Kobe earthquake data is employed to investigate the effect of various parameters for TLCD device. Figure 3 shows Kobe earthquake acceleration spectrum, which was about 7 Richter and occurred in 16th January 1995 in Kobe. The objective is to decrease the maximum absolute and root mean square (RMS) values of the displacement and acceleration of stories during earthquake oscillation.

### 4. RESULTS AND DISCUSSIONS

Considering that increasing the mass ratio of TLCD to structure would increase the efficiency of TLCD [11, 12], the mass ratio is set constant as 6.5% of the first modal mass in all cases. In order to investigate the effects of different parameters, two cases are studied: the TLCD-PA with and without pendulum. The air volume in the air room is assumed 20m$^3$ with atmospheric pressure, therefore; $k_a = 14(A_h / L_h)$ is obtained.
Considering the TLCD-PA without pendulum and valve, the design parameters are assumed as: the length ratios \((n_1, n_2)\), the cross sectional ratios \((r_1, r_2)\) and the length of horizontal column \((L_h)\). Table 3 shows the approximated best values of these parameters for decreasing the maximum absolute and RMS values of displacement and acceleration.

**Table 3: The optimized TLCD-PA parameters**

<table>
<thead>
<tr>
<th>Best Values</th>
<th>Absolute Values</th>
<th>RMS Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(u_{\text{max}})</td>
<td>(u'_{\text{max}})</td>
</tr>
<tr>
<td>Without Pendulum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n_1)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>(n_2)</td>
<td>0.6</td>
<td>2.6</td>
</tr>
<tr>
<td>(r_1)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>(r_2)</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>(L_h) (m)</td>
<td>10.75</td>
<td>40</td>
</tr>
<tr>
<td>(\eta_h)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(\omega_1) (rad/s)</td>
<td>12.25</td>
<td>3.05</td>
</tr>
<tr>
<td>(\omega_2) (rad/s)</td>
<td>46.74</td>
<td>0.75</td>
</tr>
<tr>
<td>With Pendulum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n_1=n_2)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>(r_1=r_2)</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>(L_h) (m)</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>(m_p) (kg)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>(k_{\text{co}}) (N/m)</td>
<td>200200</td>
<td>200200</td>
</tr>
<tr>
<td>(L_p) (m)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>(\omega_1) (rad/s)</td>
<td>12.34</td>
<td>4.51</td>
</tr>
<tr>
<td>(\omega_2) (rad/s)</td>
<td>44.32</td>
<td>12.63</td>
</tr>
</tbody>
</table>

This table indicates that except for the maximum value of acceleration, the minimum quantities are obtained when \(n_1\) and \(n_2\) are decreased to the least possible quantity, \(r_1\approx0.7-1\), \(r_2\approx1.1\) and \(L_h\approx11\)m. It implies that the best results are obtained when \(n_1\approx12\) (m), \(L_h\approx11\)m and \(\omega_1\approx12\) (rad/s) and \(\omega_2\approx45\) (rad/s). However, the best values of acceleration are achieved when \(n_1\) and \(n_2\) are reduced to the least feasible values, \(n_1=0.1\), \(n_2=0.1\) and \(L_h=11\)m. It states that the minimum acceleration is gained when \(\omega_1=3\) (rad/s) and \(\omega_2=0.75\) (rad/s). The head loss coefficients are assumed as \(\eta_h=\eta_r=30\) in all cases.

Figure 4 shows the changes of maximum absolute value of displacement with \(L_h\) and \(n_1\), and figure 5 shows these changes with \(L_h\) and \(n_2\) quantities. The other parameters are set as those described in Table 3. As it can be seen in these figures, the maximum displacement is decreased when \(L_h=11\)m and \(n_1, n_2\) are reduced. The effect of \(r_1\) and \(r_2\) ratios on the maximum displacement is presented in figure 6, for \(n_1=n_2=0.1\) and \(L_h=10.75\)m. According to this figure, the displacement is decreased by reducing \(r_1\) and \(r_2\) up to unity, and later it is increased. Therefore, the least quantities are obtained when \(r_1=0.8\) and \(r_2=1.1\); as mentioned before.
In order to investigate the effect of head loss coefficients, the other design variables are set as those obtained previously for the absolute value of displacement. According to Table 3, the best head loss coefficients for absolute quantities are \( \eta_h=\eta_f=0 \); and for RMS quantities are \( \eta_h=15 \) and \( \eta_f=0 \). However, assuming \( \eta_h=\eta_f=30 \) brings less than 2% error in the results. Figure 7 shows the effect of \( \eta_h \) and \( \eta_f \) on the RMS values of displacement, for the variables adjusted similar to the quantities presented in Table 3.

Considering the TLCD-PA with pendulum and valve, the design parameters are assumed as: the length ratio \( (n_1=n_2) \), the cross sectional ratio \( (r_1=r_2) \), the length of horizontal column \( (L_h) \), the pendulum mass, length and spring stiffness \( (m_p, L_p, k_{p}) \). According to the previous results, the length ratios and cross sectional ratios are supposed to be the same for the TLCD and PA equipment. It is also assumed that \( L_{co}=0.2L_p \), \( h_r=1 \)m and \( m_r=0.8A_f\times7800 \) kg; where \( t_r=0.01 \)m is the valve thickness. Table 3 shows the approximated best values for decreasing the maximum absolute and RMS values of displacement and acceleration. According to this table, the minimum values are obtained when \( n_1 \) and \( n_2 \) are decreased to the least feasible quantity, \( r_1=r_2=0.7 \) and \( L_h=30 \)m. Moreover, the pendulum mass is to be reduced, while the spring stiffness and pendulum length should be enhanced. It implies that except for absolute acceleration values, the best results are obtained when \( \omega_1=12 \) (rad/s) and \( \omega_2=45 \) (rad/s). The head loss coefficients are assumed as \( \eta_h=\eta_f=30 \) in all cases.

Figure 8 shows the changes of maximum value of displacement with \( L_h \) and \( r_1=r_2 \) ratios. The other variables are set based on Table 3. It can be seen that there is a close relationship between the proper cross sectional ratio and horizontal column length. In general, \( L_h \) is to be reduced by the increment of \( r_1=r_2 \) ratios. The effect of \( L_p \) and \( L_h \) on the maximum displacement is presented in figure 9, while the other parameters are adjusted to the best settings offered in Table 3. According to this figure, the best values of displacement are achieved when \( L_h=10 \)m. It is also notable that the maximum displacement is slightly decreased by the increment of \( L_p \).

Table 4 shows the maximum values of the objective functions for the structure with and without TLCD-PA equipment. According to this table, the maximum feasible reduction is generally increased by using the pendulum, if its parameters are set properly.

<table>
<thead>
<tr>
<th>Best Values</th>
<th>Absolute Values</th>
<th>RMS Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Results</td>
<td>%Reduction</td>
</tr>
<tr>
<td></td>
<td>( \mu_{max} )</td>
<td>( \nu_{max} )</td>
</tr>
<tr>
<td>TLCD-PA Without Pendulum</td>
<td>0.6433</td>
<td>6.6825</td>
</tr>
<tr>
<td></td>
<td>0.1882</td>
<td>1.3415</td>
</tr>
<tr>
<td>TLCD-PA With Pendulum</td>
<td>0.6331</td>
<td>6.7039</td>
</tr>
<tr>
<td></td>
<td>0.1821</td>
<td>1.3336</td>
</tr>
<tr>
<td>without TLCD-PA</td>
<td>0.7386</td>
<td>6.7744</td>
</tr>
<tr>
<td></td>
<td>0.2608</td>
<td>1.4450</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In this paper, the mathematical model of high-rise structure with TLCD-PA equipment is developed to obtain the earthquake responses. Since the damping of TLCD-PA device is a nonlinear term, the nonlinear Newmark method is employed to perform the time history analysis. The cross sectional ratios, length ratios, head loss coefficients and horizontal column length and pendulum parameters such as mass, spring stiffness and length of the pendulum are assumed as the design variables, and the objective is to decrease the maximum absolute and RMS values of displacement and acceleration.

The effect of TLCD-PA with and without pendulum is investigated. The results show that the best reduction in displacement RMS and absolute values and the RMS of acceleration is obtained when the cross sectional ratios approach unity, the length ratios are decreased to the least possible quantity and the length of
horizontal column is about 10m. It is dedicated that the greater spring stiffness and smaller mass of pendulum brings better results. However, the absolute value of acceleration is to be studied individually. It is also shown that the TLCD-PA is an advantageous device for earthquake vibration mitigation of high-rise buildings. This study improves the understanding of earthquake oscillations regarding soil effects, and helps the designers to achieve the optimized TLCD for high-rise buildings.

6. REFERENCES